

## Nanobeam production with the multicusp ion source

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(Presented on 6 September 1999)

A 1.8-cm-diam multicusp ion source to be used for focused ion beam applications has been tested for Xe, He, Ne, Ar, and Kr ions. The extractable ion and electron currents were measured. The extractable ion current is similar for all these ion species except for Ne<sup>+</sup>, but the extractable electron current behaves quite differently. The multicusp ion source will be used with a combined extractor–collimator electrode system that can provide a few hundred nA of Xe<sup>+</sup> or Kr<sup>+</sup> ions. Ion optics computation indicates that these beams can be further focused with an electrostatic column to a beam spot size of ~100 nm. © 2000 American Institute of Physics. [S0034-6748(00)58402-0]

### INTRODUCTION

The multicusp ion source developed at the Lawrence Berkeley National Laboratory (LBNL) has been used for producing high and medium current ion beams for fusion and various accelerator applications. Currently, the growing semiconductor industry is also finding use for the multicusp source, most recently in focused ion beam (FIB) systems. In FIB, an ion source is combined with an extraction column that transports and focuses the beam onto the target. Focused ion beam systems can be used for circuit inspection, mask repair, micro machining, ion doping, and direct resist writing depending on the ion species and beam spot size.<sup>1</sup> Mostly FIB systems employ a liquid metal (gallium) ion source (LMIS) and with more difficulty gaseous field ion sources (GFISs). Both of these sources have a low current yield (tens of pA), and in the case of the LMIS a large axial energy spread (>5 eV).<sup>2</sup> Until recently, only the LMIS was able to yield a very low virtual source size and/or high spectral brightness to make them attractive for FIBs. Other plasma sources fall short in performance in terms of spectral brightness. Spectral brightness is defined as

$$\beta_s = \frac{I_\Omega}{d_v \Delta E}, \quad (1)$$

where  $I_\Omega$  is the angular current density,  $d_v$  is the virtual source size, and  $\Delta E$  is the ion energy spread. An extraction configuration has been devised to be used with the multicusp ion source that can enhance its performance to a level comparable to that of the LMIS. This is possible because of the characteristic of low axial ion energy spread of the multicusp source.

A 1.8-cm-diam multicusp ion source has been tested for FIB applications at LBNL. This source can provide Xe<sup>+</sup> and Kr<sup>+</sup> ions of a few hundred nA with low axial energy spread (<2 eV) and a small virtual source size (~1 μm). The virtual source size, a limiting factor in focusing the beam into sub-micron spot diameters, has been improved at least by a factor of 10 through the use of a combined extractor–collimator electrode system.<sup>3</sup> With this arrangement and in combination

with a focusing electrostatic column, a beam spot size of 100 nm could be expected. The performance, reliability, and convenience of the multicusp ion source may eventually surpass those of the LMIS and GFIS in a FIB system.

### EXPERIMENTAL SETUP

The filament driven multicusp ion source tested has a 1.8 cm inside chamber diameter and is 3.5 cm long. A schematic of the source is shown in Fig. 1. There are 10 columns of SmCo magnets surrounding the body with alternating polarities to generate the cusp field for electron confinement. Water cooling for the source is provided only at the backplate. This small source is equipped with a magnetic filter, the advantages of which have already been published.<sup>4</sup> The plasma electrode has a 1-mm-diam round aperture. The extraction gap was set to 1 mm. Krypton, argon, neon, xenon, and helium plasmas were used to produce the electron as well as the ion beams. The pressure of the vacuum chamber was maintained constant for all of gases. The source was operated at a discharge voltage of 40 V, unless otherwise specified.

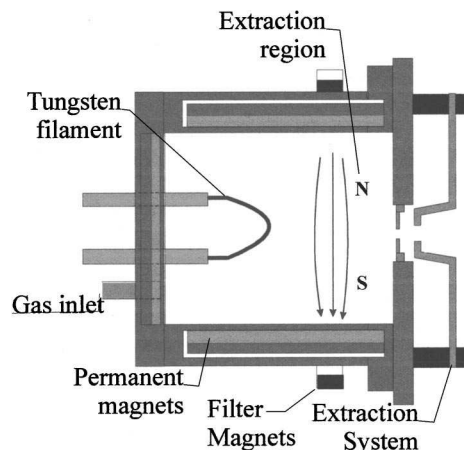


FIG. 1. Schematic of the small source.

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TABLE I. Comparisons for different gases.

Gases	Helium	Neon	Argon	Krypton	Xenon
Mass (rounded)	4	20	40	84	132
$\sigma_i$ at 40 eV ( $\pi a_0^2$ ) where $a_0$ is the Bohr radius	0.2	0.3	2.5	4	5
$\frac{1}{\sqrt{M_i}}$	0.5	0.22	0.16	0.11	0.09
$\frac{\sigma_i}{\sqrt{M_i}}$	0.1	0.07	0.4	0.44	0.45
$J_i$ (mA/cm <sup>2</sup> )	10.7	6.4	9.8	9.6	9

## RESULTS AND DISCUSSION

The extracted electron beam current has been measured for five different gases: helium, neon, argon, krypton, and xenon. Helium has the lowest ionization cross section, and xenon has the highest (Table I). Figure 2 shows the electron beam currents for these gases. Xenon has the highest electron current followed by krypton, helium, argon, and neon. Electron currents were measured with the presence of a filter that modifies the shape of the plasma potential distribution.<sup>4</sup> The extractable electron current density depends on the electron density in front of the exit aperture. Without the filter, the electron current would consist of the primary and Maxwellian electrons. Primary electrons cannot penetrate into the extraction region when the magnetic filter is present. Cold electrons can diffuse into the extraction region by coupling with the ions. The electron current for helium, argon, and krypton has been measured without the magnetic filter. The current was highest for krypton followed by argon and helium.

The ion current density also depends on the ion density in front of the exit hole. The ion current density  $J_i$  at the exit aperture is proportional to the maximum ion density  $n_i$  in the source chamber and to

$$\sqrt{\frac{kT_e}{M_i}},$$

where  $kT_e$  is the electron temperature and  $M_i$  is the ion mass.

$$J_i \propto n_i e \sqrt{\frac{kT_e}{M_i}}. \quad (2)$$

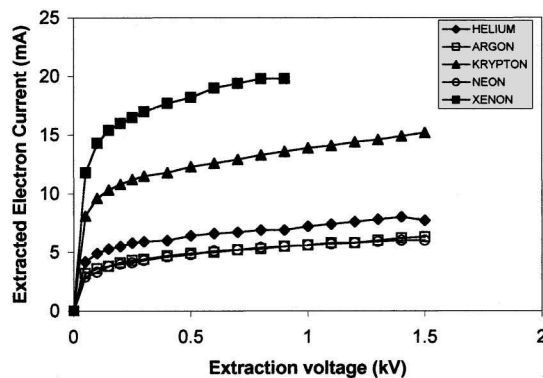


FIG. 2. Electron beam current generated from helium, neon, argon, krypton, or xenon plasmas.

$n_i \propto \sigma_i n_0$  where  $\sigma_i$  is the ionization cross section and  $n_0$  is the neutral gas density. Therefore

$$J_i \propto \sigma_i n_0 e \sqrt{\frac{kT_e}{M_i}}. \quad (3)$$

Figure 3 shows a plot of the ion current for the different gases. Except for neon, the extracted ion currents for helium, argon, krypton, and xenon are similar. Although the ion speed is slower when the mass is higher, the ion density compensates such that the extracted ion current is similar for these gases. Only neon does not follow the expected trend that the other gases do. Since small differences in pumping speed due to the different masses have not been taken into account; the discrepancy between the measured ion current and the computed  $\sigma_i / \sqrt{M_i}$  for helium (Table I) may be due to the fact that  $n_0$  is different when the source is operated with He or Ne.

The ion source was also tested with a combined extractor-collimator electrode. The collimator size is 200  $\mu\text{m}$  in diameter. A krypton beam current of 200 nA was extracted at a discharge power of 40 W. The final beam spot size was not measured, however it is expected to be below 100 nm.

## SUMMARY

A small filament driven multicusp ion source is the base for the next generation in gaseous sources for focused ion beams. It can generate any type of gaseous ions with im-

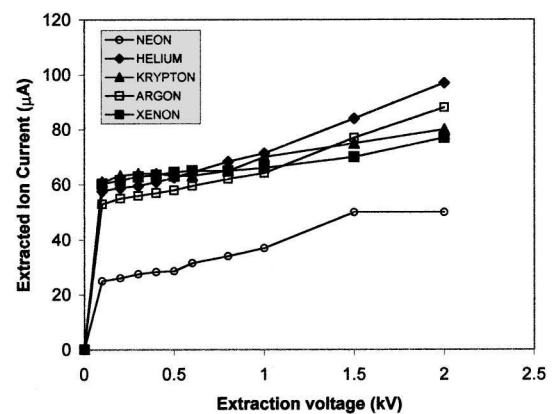


FIG. 3. Ion beam current generated from helium, neon, argon, krypton, or xenon plasmas.

proved ion beam current better than any other source for FIB. Krypton will be used for a similar size source to be used for ion milling and machining. An ion current of 200 nA is more than sufficient for the purpose. The same source can be used to produce high brightness electron beams for lithography or electron microscope applications.

## ACKNOWLEDGMENTS

The authors would like to thank M. Dickinson, P. Kozy, L. Mills, T. McVeigh, P. Rosado, S. Wilde, and P. Wong.

This work was supported by DARPA, Micrion Corporation, and the U.S. Department of Energy under Contract No. De-AC03-76F00098.

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